P-wave Pairing in Two-Component Fermi System with Unequal Population near Feshbach Resonance

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We explore p-wave pairing in a single-channel two-component Fermi system with unequal population near Feshbach resonance. Our analytical and numerical study reveal a rich superfluid (SF) ground state structure as a function of imbalance. In addition to the state $\Delta_{\pm 1} \propto Y_{1\pm 1}$, a multitude of "mixed" SF states formed of linear combinations of Y_{1m}'s give global energy minimum under a phase stability condition; these states exhibit variation in energy with the relative phase between the constituent gap amplitudes. States with local energy minimum are also obtained. We provide a geometric representation of the states. A T=0 polarization vs. p-wave coupling phase diagram is constructed across the BEC-BCS regimes. With increased polarization, the global minimum SF state may undergo a quantum phase transition to the local minimum SF state.

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Introduction: Discovery of s-wave paired fermion condensates in cold atoms [1] subjected to s-wave Feshbach resonance (FR) have led to explorations in several fascinating directions. One is the study of superfluidity in asymmetrical Fermi systems, a subject of intense experimental and theoretical research [2, 3, 4]. Another is the prospect for attaining fermion condensates with pairs having non-zero relative orbital angular momentum. Recent observations of p-wave FR [5, 6, 7, 8] in ^6Li and ^{40}K have raised the possibility of observing p-wave superfluidity in cold atoms, leading to renewed theoretical interest. P-wave superfluidity in the BEC-BCS crossover region has been studied using fermion-boson models applied to single-component Fermi gas (where FR occurs in the same hyperfine state) [9, 10], and using fermion-only models at T=0 both in two-component Fermi gas (where FR occurs between different hyperfine states) [11] and in single-component case [12]. Ohashi [13] considered both cases at finite-T. While there have been fervent theoretical efforts [3, 4] on pairing in asymmetrical Fermi systems subject to s-wave FR, work on the corresponding p-wave case is lacking.

In this paper, within a fermion-only model, we study p-wave superfluidity near a p-wave FR in a two-component Fermi system with *unequal* populations in two hyperfine states. It is conceivable that in future, population imbalanced systems under p-wave FR would be realized similar to the ones subject to s-wave FR. We hope that this work will motivate experimental efforts.

It has been pointed out [7, 11] that unlike liquid ^3He, pairing interaction in cold atoms is highly anisotropic in "spin"-space. ("spin" referring to hyperfine states). For example, in ^6Li, when the hyperfine pair $|1/2, -1/2>$ is at resonance, the pairs $|1/2, 1/2>$ and $|-1/2, -1/2>$ would not be. So, in studying pairing in this two-component system, intra-spin interactions need not be considered. Pairs in p-wave superfluids with unlike "spin" components can however have different orbital angular momentum content, so the gap parameters $\Delta_{lm} \propto \ell = 1$ spherical harmonics Y_{1m} $(m = \pm 1, 0)$.

Our analytic and numerical considerations of the population imbalanced system lead to several interesting results and predictions: (i) We find a rich superfluid ground state (GS) structure: The p-wave state Δ_1(hence Δ_{-1} by symmetry) give a GS *global* minimum energy. Interestingly, under a specific condition involving the relative phases of the three pairing amplitudes Δ_m's, a multitude of "mixed" states of the form $a\Delta_0 + b\Delta_1 + c\Delta_{-1}$ ($\Delta_{1m} \equiv \Delta_m$ here) are degenerate with $\Delta_{\pm 1}$. In addition, we find states with *local* energy minimum. (ii) We provide a geometric representation of the p-wave superfluid states (Fig 1): The states exhibiting global minimum lie on a "semicircle" formed by the intersection of the surface of the sphere formed by $\Delta_1, \Delta_{-1}, \Delta_0$ with a plane defined by $|\Delta_1| + |\Delta_{-1}| =$ const. (iii) We obtain polarization (P) vs p-wave coupling phase diagram at T=0. (Fig 2). The superfluid phase SF1 comprises of states with global minimum, while SF2 of states with the local minimum. We also find a region of phase separation PS between SF2 and the normal phase N. In this two-component system, PS persists onto full polarization. (iv) These raise the intriguing possibility for a T=0 quantum phase transition from SF1 to SF2 at finite polarization (Fig 2). Additionally, transitions at finite-T would also occur. (v) In the limit $P \to 0$, we find that the ground state structure of $P \neq 0$, is preserved, hence richer than that obtained earlier [11].

Model: We consider a two-component Fermi system with unequal "spin" $(\uparrow, \downarrow)$ population, but equal masses for the unlike fermions. We take the interaction between unlike fermions to be isotropic in orbital space. Following the rationale above, interactions between like fermions are taken to be zero. Since we adjust self-consistently the chemical potential with the strength and sign of the coupling, in our fermion-only model, molecules would naturally appear as 2-fermion bound states. The pairing

Hamiltonian is then given by:

$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}\sigma} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}\mathbf{k}'\mathbf{q}} V_{\mathbf{k}\mathbf{k}'} c^\dagger_{\mathbf{k}+\mathbf{q}/2\uparrow} c^\dagger_{-\mathbf{k}+\mathbf{q}/2\downarrow} c_{-\mathbf{k}'+\mathbf{q}/2\downarrow} c_{\mathbf{k}'+\mathbf{q}/2\uparrow} \quad (1)$$

where $c_{\mathbf{k}\sigma}$ ($c^\dagger_{\mathbf{k}\sigma}$) is the annihilation (creation) operator for a fermion with momentum $\mathbf{k}$, kinetic energy $\xi_{\mathbf{k}\sigma}=\epsilon_{\mathbf{k}}-\mu_\sigma$, and spin σ $(=\uparrow,\downarrow)$; μ_σ is the chemical potential of each component, and $\epsilon_{\mathbf{k}}=\hbar^2k^2/2m$.

We consider condensate pairs with zero center-of-mass momentum, ($\mathbf{q}$=0). $\mathcal{H}$ is mean-field (MF) decoupled via the "spin"-triplet ($S=1, m_s=0$) pairing gap function $\Delta_{\downarrow\uparrow}(\mathbf{k}) \equiv \Delta(\mathbf{k}) = -\sum_{\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'}\langle c_{-\mathbf{k}'\uparrow} c_{\mathbf{k}'\downarrow}\rangle$ giving:

$$\begin{aligned}\mathcal{H}^{\mathrm{MF}} &= \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}\sigma} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} \\ &- \sum_{\mathbf{k}} \left[\Delta(\mathbf{k}) c^\dagger_{\mathbf{k}\uparrow} c^\dagger_{-\mathbf{k}\downarrow} + \mathrm{H.c.}\right] \\ &- \sum_{\mathbf{k}} |\Delta(\mathbf{k})|^2 / V_{\mathbf{k}\mathbf{k}} \qquad (2)\end{aligned}$$

To obtain the variational ground state energy of the MF Hamiltonian (2) we use the equation-of-motion method [4] for the imaginary-time ($\tau = it$) normal ($G_{\sigma\sigma'}$) and anomalous ($F_{\sigma\sigma'}$) Green's functions:

$$\begin{aligned}\partial_\tau G_{\sigma\sigma'}(\mathbf{k},\tau) &= -\delta(\tau)\delta_{\sigma\sigma'} - \xi_{\mathbf{k}\sigma} G_{\sigma\sigma'}(\mathbf{k},\tau) \\ &+ \Delta_{-\sigma\sigma}(\mathbf{k}) F_{-\sigma\sigma'}(\mathbf{k},\tau), \qquad (3)\\ \partial_\tau F_{\sigma\sigma'}(\mathbf{k},\tau) &= \xi_{-\mathbf{k}\sigma} F_{\sigma\sigma'}(\mathbf{k},\tau) \\ &+ \Delta^*_{\sigma-\sigma}(\mathbf{k}) G_{-\sigma\sigma'}(\mathbf{k},\tau). \qquad (4)\end{aligned}$$

Eqs. (3) and (4) are Fourier transformed with $\tau\to i\omega_n\equiv\nu$ and $\partial_\tau\to-\nu$, where $i\omega_n=(2n+1)\pi T$ are Matsubara frequencies. This gives $G_{\sigma\sigma}(\mathbf{k},\nu) = -(\xi_{-\mathbf{k}-\sigma}+\nu)/\left[(\xi_{\mathbf{k}\sigma}-\nu)(\xi_{-\mathbf{k}-\sigma}+\nu)+|\Delta_{\sigma,-\sigma}(\mathbf{k})|^2\right]$ and $F_{\sigma-\sigma}(\mathbf{k},\nu)=\Delta^*_{\sigma-\sigma}(\mathbf{k})/[(\xi_{\mathbf{k}-\sigma}-\nu)(\xi_{-\mathbf{k}\sigma}+\nu)+|\Delta_{\sigma-\sigma}(\mathbf{k})|^2] = -F_{-\sigma\sigma}(\mathbf{k},\nu)$.

We separate the radial and angular parts of the interaction potential: $V_{\mathbf{k}\mathbf{k}'} = (4\pi/3)\sum_m V_{kk'} Y_{1,m}(\hat{\mathbf{k}}) Y^*_{1,m}(\hat{\mathbf{k}}')$ ($\hat{\mathbf{k}}=(\theta,\phi)$), and take for $V_{kk'}$ a separable form convenient for analytic calculations: $V_{kk'} = \lambda w(k) w(k')$. Using $\langle c_{-\mathbf{k}'\downarrow} c_{\mathbf{k}'\uparrow}\rangle \equiv F^*_{\downarrow\uparrow}(\mathbf{k}',\tau=0^-)$ and Fourier transforming, we obtain for the gap function, $\Delta(\mathbf{k}) = -(1/k_BT)\sum_{\nu\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'} F^*_{\downarrow\uparrow}(\mathbf{k}',\nu) e^{\nu 0^+}$. With the separable form of $V_{kk'}$, the gap function can be written as: $\Delta(\mathbf{k}) = \sum_m \Delta_m w(k) Y_{1m}(\hat{\mathbf{k}}) \equiv w(k)\Delta(\hat{k})$, where $\Delta_m = -(1/k_BT)\sum_{\nu\mathbf{k}'} \lambda w(k') Y^*_{1m}(\hat{\mathbf{k}}') F^*_{\downarrow\uparrow}(k',\nu) e^{\nu 0^+}$. With $F_{\downarrow\uparrow}(k,\nu)$ known, we finally obtain the equations for the gap amplitudes ($m = 0, \pm 1$),

$$\Delta_m = -\lambda \sum_{\mathbf{k}} w(k) Y^*_{1m}(\hat{\mathbf{k}}) \Delta(\mathbf{k}) [n_F(E^-_k) - n_F(E^+_k)]/(2E_k) \qquad (5)$$

where $E^\pm_k = -h \pm E_k$, $h = (\xi_{k\downarrow} - \xi_{k\uparrow})/2 = (\mu_\uparrow - \mu_\downarrow)/2$, $E_k = [\xi_k^2 + |\Delta^2(\mathbf{k})|]^{1/2}$, with $\xi_k=(\xi_{k\uparrow}+\xi_{k\downarrow})/2=\epsilon_k-\mu$ and $\mu=(\mu_\uparrow+\mu_\downarrow)/2$; $n_F(E^\pm_k)$ are Fermi functions. We can now average (2) and calculate the variational ground-state energy E_G. At T=0 and for h>0 this is given by:

$$\begin{aligned}E_G \equiv \langle\mathcal{H}\rangle &= \sum_k \left\{\xi_k - E_k + \frac{|\Delta(\mathbf{k})|^2}{2\epsilon_k}\right\} \\ &+ \sum_k \{(E_k - h)\theta(-E_k + h)\} - \frac{1}{g}\sum_m |\Delta_m|^2, \quad (6)\end{aligned}$$

where the regularized interaction g is given by $1/g = 1/\lambda + (1/(2\pi\hbar)^3)\int w^2(k) d^3\mathbf{k}/2\epsilon_k$.

Ground State Analysis: First, we carry out an analytic study of the p-wave superfluid ground state structure. We assume $|\Delta(\mathbf{k})| \ll E_k$, and expand E_k in powers of $|\Delta(\mathbf{k})|$ keeping terms to 4th order: $E_k \sim |\xi_k|[1+|\Delta(\mathbf{k})|^2/2\xi_k^2 - |\Delta(\mathbf{k})|^4/8\xi_k^4]$. Substituting this expression for E_k in (6) and converting momentum sums to integrals we obtain a simple representation for $E_G = \alpha\int|\Delta(\hat{k})|^2 d\Omega + \beta\int|\Delta(\hat{k})|^4 d\Omega + \gamma$, where $\alpha = (1/(2\pi\hbar)^3)\int_{E_k<h} w^2(k)k^2dk/2\epsilon_k + (1/(2\pi\hbar)^3)\int_{E_k>h} w^2(k)k^2dk(1/2\epsilon_k - 1/2\xi_k) - 1/g$, $\beta = (1/(2\pi\hbar)^3)\int_{E_k>h} w^4(k)k^2dk/8|\xi_k|^3$ and $\gamma = (4\pi/(2\pi\hbar)^3)\int_{E_k<h}(\xi_k - h)k^2dk$. Existence of a superfluid phase requires α<0, otherwise minimization of E_G forces the gap to vanishes. The polarization ($P = (n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow)$) dependence of E_G is contained in α,β,γ, which depend on $h,\mu,w(k)$, while α alone depends explicitly on the coupling g. Owing to these dependences the gap parameters are sensitive to changes in P.

For fixed μ and h, and E_k given above, the ground state energy E_G is obtained by minimizing (6) with respect to the pairing amplitudes Δ_m. Thus we arrive at an analytic expression for the ground state energy [14]:

$$\begin{aligned}E_G = -\frac{\alpha^2}{8\beta} + \gamma + 2\beta\left(|\Delta_0|^2 + |\Delta_1|^2 + |\Delta_{-1}|^2 + \frac{\alpha}{4\beta}\right)^2 \\ + \beta(|\Delta_0|^2 - 2|\Delta_1||\Delta_{-1}|)^2 + 4\beta(1-t)|\Delta_0|^2|\Delta_1||\Delta_{-1}| \quad (7)\end{aligned}$$

where t=$\cos\theta$, with $\theta = \cos^{-1}(\Delta_0\Delta_1^*, \Delta_0^*\Delta_{-1}) = (2\phi_0 - \phi_1 - \phi_{-1})$; ϕ_m's are the phases associated with the gap amplitudes Δ_m. From (7), we find that for a stable p-wave superfluid phase to exist, the following conditions have to be satisfied simultaneously

$$\begin{aligned}(a)\quad & |\Delta_0|^2 + |\Delta_1|^2 + |\Delta_{-1}|^2 = -\alpha/4\beta \\ (b)\quad & |\Delta_0|^2 - 2|\Delta_1||\Delta_{-1}| = 0 \qquad (8)\\ (c)\quad & (1-t)|\Delta_0|^2|\Delta_1||\Delta_{-1}| = 0\end{aligned}$$

giving the GS *global minimum* energy

$$E_G = -\alpha^2/8\beta + \gamma. \qquad (9)$$

Conditions (a) and (b) together represent a semicircle

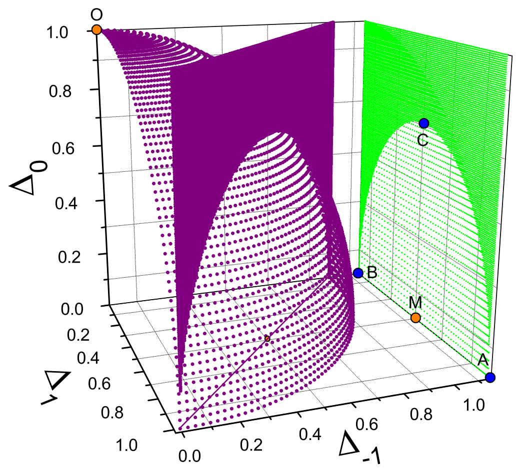

FIG. 1: (Color online) Geometric representation of p-wave states in two-component population imbalanced system. States (e.g. A, B, C) exhibiting global energy minimum lie on the semicircle formed by the intersection of sphere surface with plane (see text). For clarity, plane containing semicircle is also shown separately (green). O (north pole) and M (on Δ_1-Δ_{-1} plane) are states with local energy minimum. $\Delta_m(m = 0, \pm 1)$'s have been normalized to the sphere radius $\sqrt{-\alpha/4\beta}$; $\alpha < 0$.

formed by the intersection of the surface of a sphere of radius R, $R^2 = -\alpha/4\beta$, with a plane defined by $|\Delta_1| + |\Delta_{-1}|{=}R$. All points on the semicircle must necessarily satisfy the phase constraint (c). They represent a multitude of "mixed" superfluid states of the form $a\Delta_0 + b\Delta_1 + c\Delta_{-1}$. A 3D geometric representation of the states is shown in Fig. 1. The GS global energy minimum condition is satisfied only for $t = 1$ in Eq. 8c, i.e. when the relative phase $\theta = ((\phi_0{-}\phi_1){-}(\phi_{-1}{-}\phi_0)) = 2n\pi$. For the states $\Delta_{\pm 1}$, (points A and B on the semicircle in Fig 1) this is always satisfied. For the other states on this curve, containing varying admixtures of Δ_m's, E_G fluctuates with θ, and attains the global minimum only for $\theta = 2n\pi$ (Fig. 3a); the fluctuation amplitude depends on the specific state chosen; e.g. C at the top of the projected figure has the maximum amplitude variation, but still lies lower than the local minimum we discuss below. $t{=}1$ corresponds to a parallel orientation of vectors $\Delta_0\Delta_1^*$ and $\Delta_0^*\Delta_{-1}$; this gives the same global minimum $E_G{=}{-}\alpha^2/8\beta + \gamma$ for three particular cases: (A) $|\Delta_0|{=}|\Delta_{-1}|{=}0$ and $|\Delta_1|^2{=}{-}\alpha/4\beta$; (B) $|\Delta_0|{=}|\Delta_1|{=}0$ and $|\Delta_{-1}|^2{=}{-}\alpha/4\beta$; (C) $|\Delta_0|^2{=}{-}\alpha/8\beta$ and $|\Delta_1|^2{=}|\Delta_{-1}|^2{=}-\alpha/16\beta$. These are shown as points A,B,C respectively in Fig. 1. In addition to these, we also find the existence of *local* minimum with $E_G^L{=}{-}\alpha^2/12\beta{+}\gamma$ for: (i) $|\Delta_0|^2{=}{-}\alpha/4\beta$ and $|\Delta_1|{=}|\Delta_{-1}|{=}0$; (ii) $|\Delta_0|{=}0$ and $|\Delta_1|^2{=}|\Delta_{-1}|^2{=}{-}\alpha/12\beta$; these are shown as O and M respectively in Fig. 1. Values for the GS energy are completely determined by α, β, and γ. In evaluating these, we take the N-SR [15] form: $w(k){=}k_0k/(k_0^2 + k^2)$, where k_0 is a cut-off momentum.

In the limit of zero polarization, $P \to 0$, the GS energy coefficient $\gamma \to 0$, while $\alpha < 0, \beta > 0$ remain finite. Thus the GS structure of the polarized case is preserved for zero polarization, with the same expressions for the energy global and local minima (different numerical values). The states A and B (equivalent to A by symmetry) above and in Fig. 1 correspond to the finding of Ref. [11]. Our work reveals an additional set of "mixed" states on the intersecting semicircle (Fig. 1) that also have the same global minimum for specific values of the relative phase discussed above.

Numerical Calculations: Guided by our analysis of the p-wave superfluid ground state, we carry out a detailed numerical study. For fixed number densities, we solve self-consistently three gap equations (Eq. 5) and two number equations given by:

$$n_\sigma = \sum_k \langle c_{k\sigma}^+ c_{k\sigma} \rangle = \sum_k G_{\sigma\sigma}(k, \tau = 0^-), \qquad (10)$$

This gives us the gap amplitudes Δ_m, and the chemical potentials μ_σ. Using these we obtain the ground state energy E_G from Eq. 6, as well as the coefficients α, β, γ that determine E_G given by Eq. 7. The agreement between our numerical E_G and our analytical E_G (based on an expansion of E_k) is good to within 15%.

We construct a polarization (P) - coupling $(1/k_F^3 a_t)$ *phase diagram* in BEC-BCS crossover regime (Fig. 2), enforcing the stability conditions: that the stability matrix $(\partial^2 E_G/\partial\Delta_{m_i}\partial\Delta_{m_j})$ is positive definite; and that $\delta p/\delta h > 0$. In Fig. 2, SF1 denotes a stable superfluid phase, corresponding to the states on the 'semicircle' in Fig. 1 that produce GS global minimum, i.e. with relative phase $\theta{=}2n\pi$ among the gap parameters. With increased polarization, at $T{=}0$, SF1 becomes unstable, and gives way to the superfluid phase SF2, corresponding to states with the local minimum discussed above. In Fig. 2, states Δ_1 and Δ_0 were chosen in SF1 and SF2 respectively; other choices of allowed global and local minimum states give qualitatively the same phase diagram. At even larger polarizations, SF2 becomes unstable to phase separation, PS. SF1, SF2, PS occupy a relatively much narrower part of the phase diagram on the BCS side compared to the BEC side. In our two-component system with inter-species interaction, PS persists into full polarization, P=1. This is reasonable because at P=1, the system is essentially a one-component system in which the absence of minority species atoms makes inter-species interaction inoperative. Such a system can exhibit superfluidity only under the effect of intra-species interactions. Our results suggest several interesting possibilities: A $T{=}0$ quantum phase transition from SF1 to SF2 driven

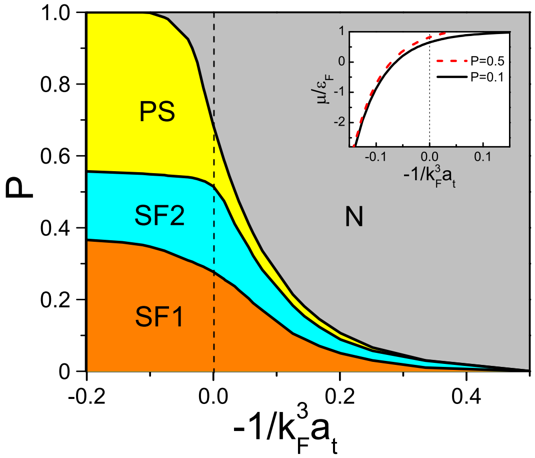

FIG. 2: (Color online) Polarization P vs p-wave coupling $-1/(k_F^3 a_t)$ phase diagram of two-component one-channel Fermi system with p-wave pairing. Shown are normal, N, and p-wave superfluid phases, SF1 and SF2, as well phase separation, PS. Unitarity limit is shown by the dashed vertical line. Inset: Calculated chemical potential vs coupling across BCS and BEC regimes for $P = 0.1$ (solid line); 0.5 (dashed line).

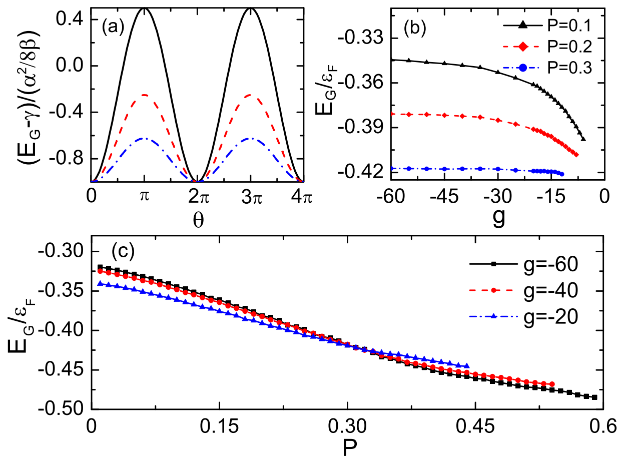

FIG. 3: (Color online) (a) Calculated ground state energy (scaled to global minimum) vs. relative phase angle θ (see text). Solid curve with maximal fluctuations of E_G corresponds to state C in Fig 1, ($|\Delta_0|^2{=}-\alpha/8\beta$, $|\Delta_1|^2{=}|\Delta_{-1}|^2{=}-\alpha/16\beta$). The dash and dot-dash curves correspond to two other states on the arc in Fig. 1: $|\Delta_0|^2{=}-\alpha/11.3\beta$, $|\Delta_1|^2{=}-\alpha/76.3\beta$, $|\Delta_{-1}|^2{=}-\alpha/6.73\beta$, and $|\Delta_0|^2{=}-\alpha/16\beta$, $|\Delta_1|^2{=}-\alpha/186\beta$, $|\Delta_{-1}|^2{=}-\alpha/5.49\beta$ respectively. (b) Calculated ground state energy vs. coupling g for different polarizations, P. (c) Calculated ground state energy vs. polarization P for different coupling strengths g.

by polarization may be expected. Since the energies of SF2 and the continuum of "mixed" states for $\theta \neq 2n\pi$ lie higher than the GS global minimum, they may be accessed at finite-T. Also, each p-wave state on the semicircle (Fig. 1) (generally formed of a linear combination of the Δ_m's except for the "pure" $\Delta_{\pm 1}$ states A,B), is characterized by a relative phase $2n\pi \leq \theta \leq (2n{+}2)\pi$. Hence, for each there is a multitude of θ-dependent states (Fig. 3a) with varying E_G that may be interesting to probe with experiments sensitive to such relative phases. The inset in Fig. 2 shows the calculated behavior of chemical potential μ across the BEC-BCS regime. It deviates significantly from the Fermi energy in a wider region around FR even on the BCS side, and drops much more rapidly to negative values on the BEC side compared to the s-wave FR case. For sufficiently weak coupling in the BCS regime, μ approaches Fermi energy ϵ_F.

Figs. 3b, 3c show the variation of E_G with coupling g $(=25k_F^3 a_t/8\pi)$ at fixed polarizations P, and with P for fixed g. E_G is normalized to the Fermi energy ϵ_F $= \hbar^2 k_F^2/2m$, with $2k_F^3 = k_{F\uparrow}^3 + k_{F\downarrow}^3$. For a given P, E_G becomes less negative as g approaches unitarity; the trend is more noticeable for smaller P's. For a given g, E_G lie higher for smaller P, presumably due to the lower majority-species band becoming progressively more occupied with increasing P, thereby lowering E_G with increasing polarization. For small P, E_G becomes less negative with increasing g. This trend is reversed for $P \geq 0.3$.

Conclusions: We believe we have presented new results and made several predictions for two-component population imbalanced Fermi systems across the entire BCS-BEC regimes. Future experiments in cold fermions near p-wave FR may be able to provide tests of some of these predictions. Insight into the nature of the orbital part of our superfluid states may be gained from measuring the angular dependence of momentum distributions; from molecular spectroscopy using light radiation; or possibly measurements of zero sound attenuation. The work could also be of interest to other two-component Fermi systems where p-wave intra-species couplings are small or negligible.

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